Distributed Architectures and Traverse Planning for Mars Exploration

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November 6, 2001

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Motivation

Distributed systems may offer

- Energy efficiency (multi-hop vs. single hop)
- Distributed data collection and sensing
- Scalability, flexibility (Saleh, 2001), robustness
- Support for robotic and human explorers

Mechanism(s)

- Spatial distribution of (homogeneous or heterogeneous) system elements
- Ability to reconfigure system (compensate for changes in environment, missions goals, or capabilities)

Distributed Architectures

Architecture
- System
- Environment
- Process to build and operate

Fundamental feature is message passing between elements of the system.

Distributed: spatial distribution

Static vs. Dynamic System: system evolution

Traverse: Operation in which one or more elements of a system cooperate to achieve a limited subset of overall mission goals while working within a set of constraints or “flight rules.” (example of intentional evolution)

Two important themes of exploration

Mobility

Delivers right capability to right place at right time

Lewis and Clark

Information management

Enables interpretation of data to support hypothesis testing and re-planning.

Exploration as World Building

How does an explorer (human/robot) use information?

How does this change when information can be shared?

Benefits of communication to exploration:

- Reduced time between discovery and sharing of results.
- Enhanced ability of explorer to adapt to obstacles by improving decision-making abilities
- Permitting “outsiders” to provide different perspectives and to participate in exploration

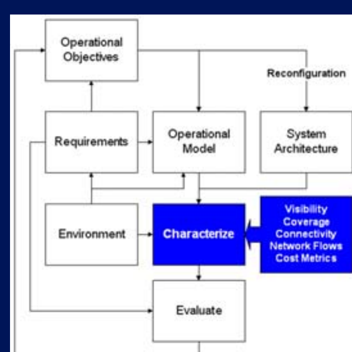
System-Level Characterization

Surface model: digital elevation model

System element (node, agent, etc.) model

Analysis needs

- Connectivity
  - line-of-sight metric
  - Apply graph theory tools
- Surface visibility
- Cost of message delivery
- Cost of mobility
- Model of system evolution
  - Traverses = spatial reconfiguration



Trades

Distributed vs. Non Distributed

Delivery Mechanism

Multi-Hop vs. Single-Hop

Network Protocol Stack →

Quality of Service

- Delay
- Bandwidth

Network Stability

Node Heterogeneity

Required network services

- Timing
- Positioning
- Concurrency Control
- Data storage/access

Layer	Adjustable Parameters
Session	Timing and duration, Message content, Reassembly process
Transport	Routing, Transfer rate and latency, Network congention control
Logical Link	Error control Flow control
Medium Access	Access timing and duration, Collision avoidance, Error avoidance
Physical	Radio Frequency Power, Antenna Gain, Pointing Requirements

Single Hop vs. Multi Hop

FRIIS Transmission equation

Transmitted power, single hop $P_{t,s} \propto (nr)^m P_r$

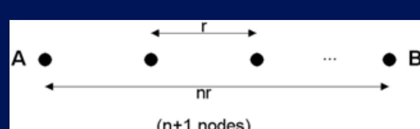
Transmitted power, multi hop $P_{t,m} \propto n r^m P_r$

m is space loss exponent (2 for free space)

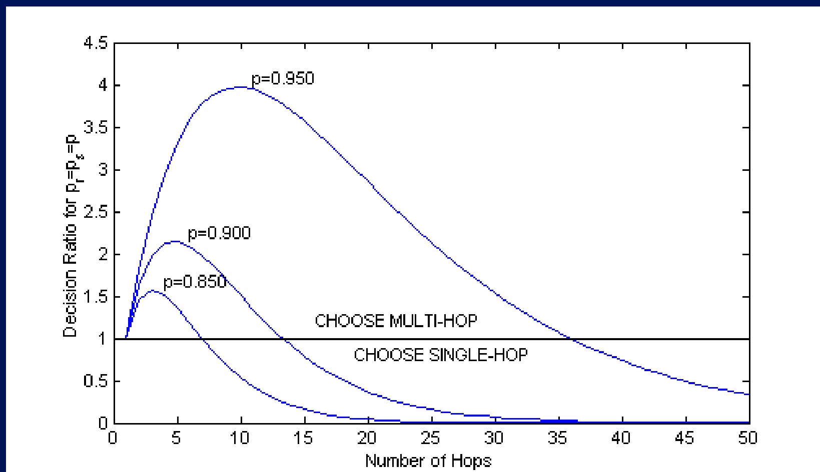
Prob(send message|received) p_s

Prob(receive message|sent) p_r

Ratio of expected power for delivery via multi-hop to single hop $\frac{E(P_{t,s})}{E(P_{t,m})} = (p_s p_r)^{n-1} n^{m-1} = R$



Single Hop vs. Multi Hop



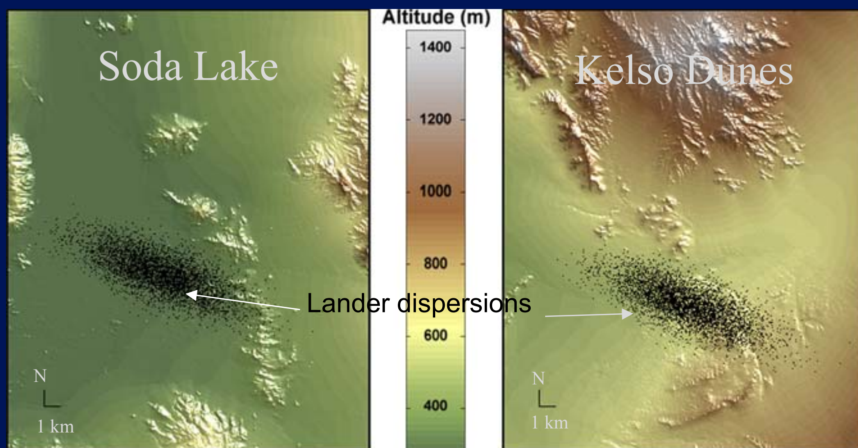
Lander and Sensor Network Example

A Mars Lander is to serve as a communication trunk for a sensor network to be deployed on an ancient lakebed. Two sites are under consideration: a smooth flat lakebed, and an area of sand dunes.

This example explores the factors involved in designing the system to meet a single requirement, that 90% of the sensor nodes should be reachable by the lander with a 90% probability.

Lander and Sensor Network Example

Representative Surface: Mojave Desert



Lander and Sensor Network Example

Parameters

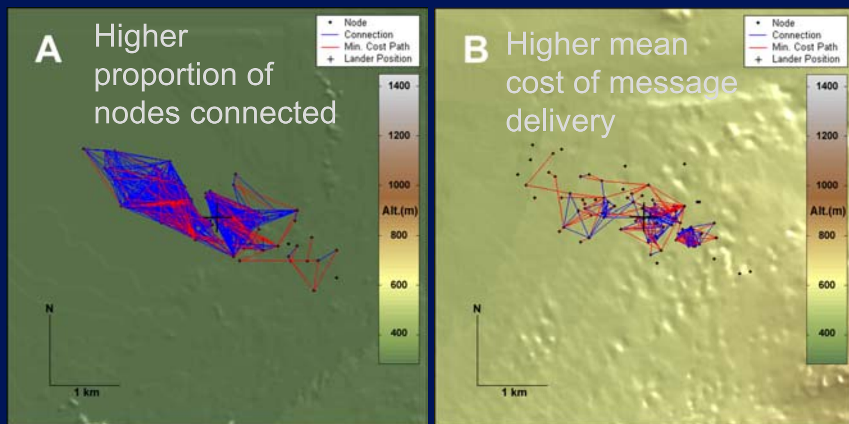
- 300 lander positions
- 100 nodes
- 2 surfaces (Soda Lake, Kelso Dunes)

Analysis

- Proportion of nodes connected to lander
- Mean cost of message delivery
  - Connectivity graph: assign edge cost $C = (r/d)^2$
  - r=distance between nodes
  - d = nominal distance between nodes
  - m=space loss exponent=2 (free space).

Lander and Sensor Network Example

Network topology: sensitive to topography.



Soda Lake | Kelso Dunes

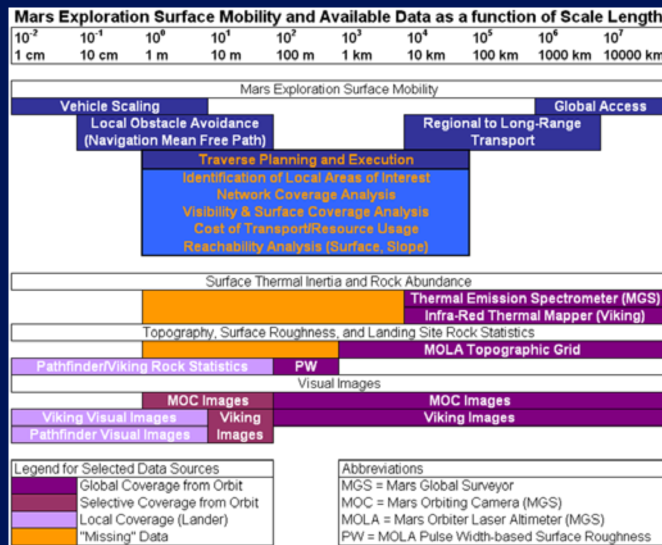
Why traverse planning?

Traverse planning

- Cost/benefit analysis for elements (human/robot)
- Quantify consumables usage, risks, etc.
- Evaluate exploration services available
  - Communications
  - Data access/storage
  - Supporting system elements
- Supports reconfiguration of a distributed system
  - Basis for selecting one route among many
  - Basis for selecting one element over another
  - Ensures compliance with “flight rules”
- Requires data-rich environment
  - Mars is a data rich environment

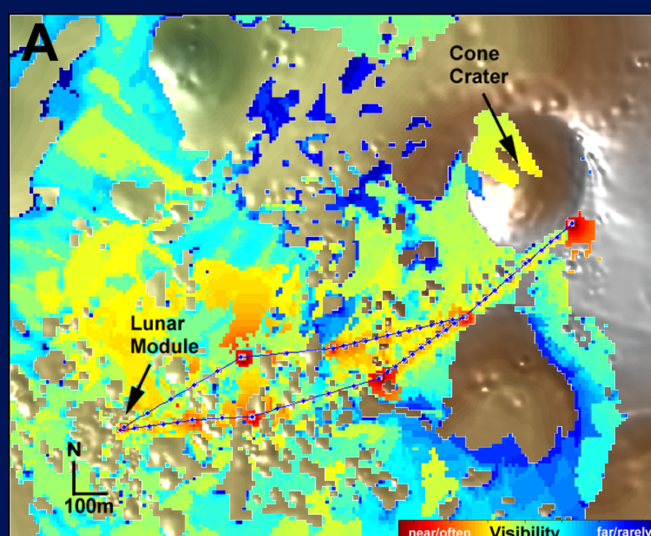
Mobility and Traverse Planning for Mars

- Exploration inherently involves uncertainty. Coping with uncertainty requires flexibility.
- "Flight rules" may impose complex system of constraints.
- Traverse planning is an approach to creating flexibility during exploration with constraints.
- Analogue to air traffic control: filing/updating a flight plan: applicable to human & robotic explorers.



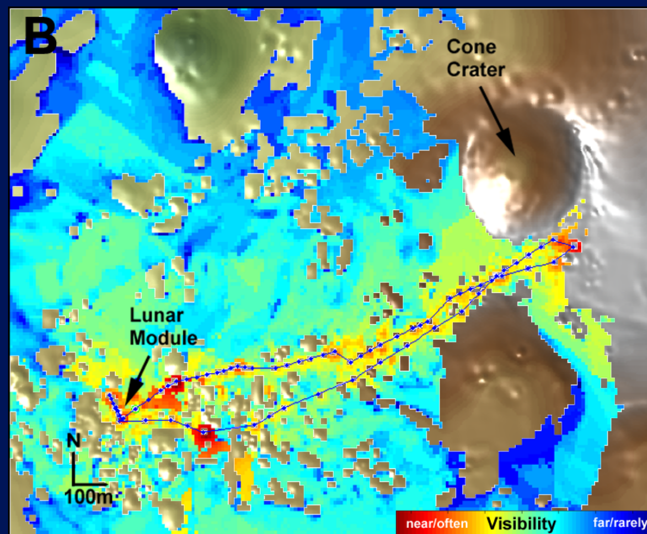
Traverse Example: Apollo 14 EVA2

Surface
Visibility
Of
Planned
Traverse

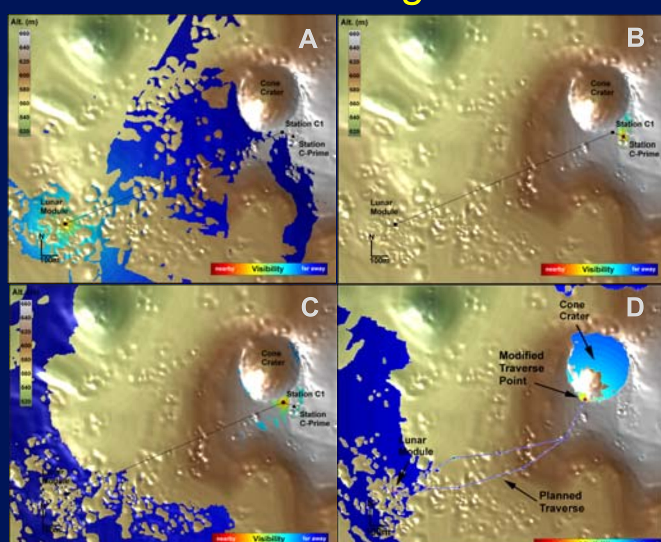


Traverse Example: Apollo 14 EVA2

Surface
Visibility
Of
Actual
Traverse



Apollo 14 EVA 2: Finding Cone Crater



Conclusions

- Distributed systems
  - Change how information is collected and disseminated during exploration: provide the support infrastructure for exploration
  - Can be characterized by performance metrics such as cost of message delivery and others…but optimization is challenging
  - May provide flexibility and robustness, but at the cost of complexity.
  - Science opportunities include
    - Spatial and temporal characterization (sensor webs)
    - Calibration of remote sensing data (K. Delin/JPL)
- Traverse planning
  - Supports evolution of a distributed system
  - Automation of traverse planning may support rapid re-planning even with complex or numerous “flight rules”
  - Especially valuable when have long light-travel-time delays (reduce “wasted” time – flight plan analogy)
  - Requires proper data, models, and the information delivery, analysis, and dissemination infrastructure

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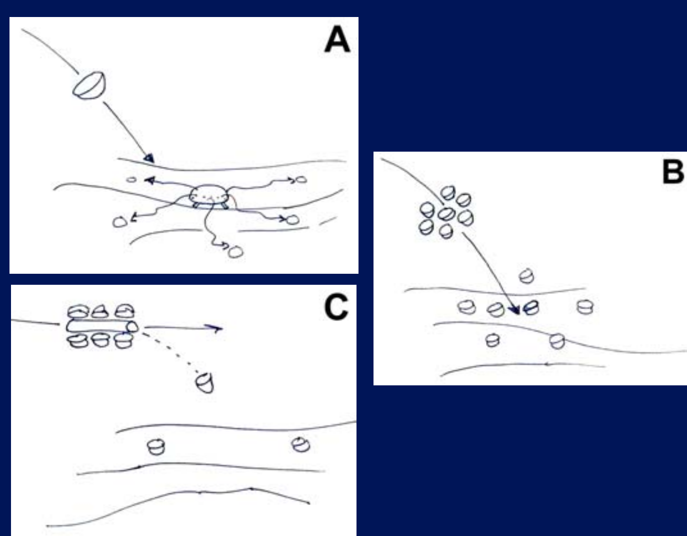
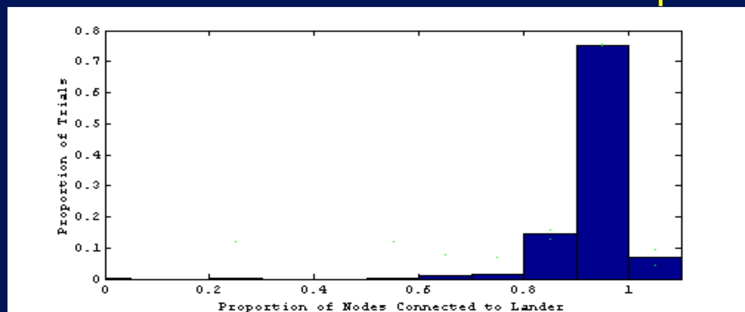
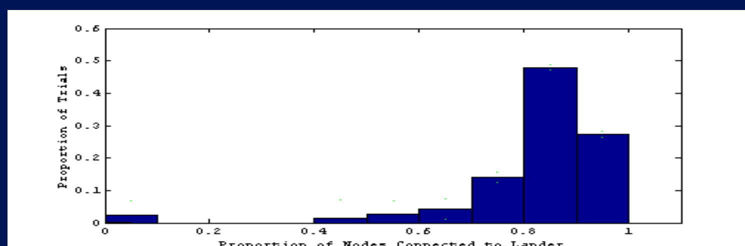
Supporting Slides

Delivery Mechanism(s)

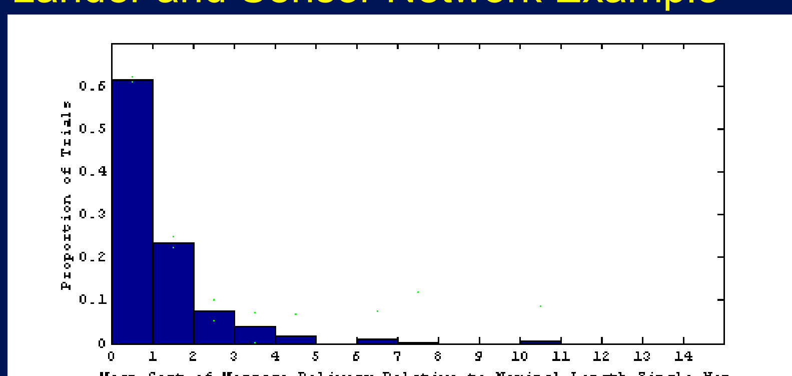


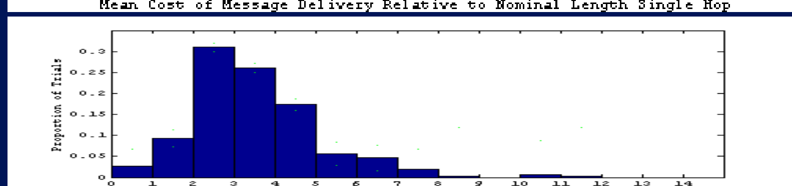
Lander and Sensor Network Example





Lander and Sensor Network Example





Process for Traverse Planning

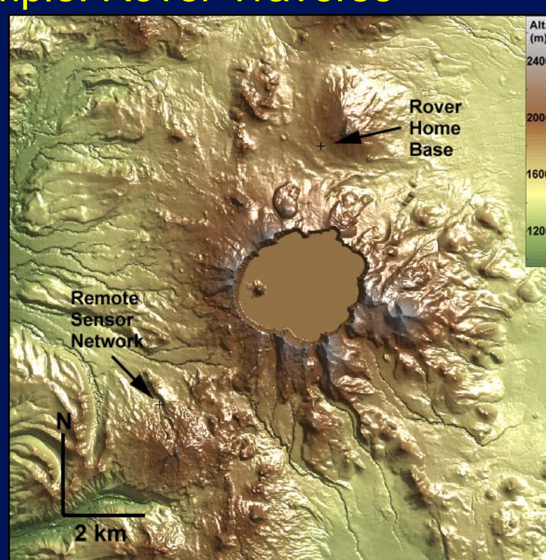
A simple framework for traverse planning

- Evaluate Path Independent Surface Conditions and Accessibility (slope, surface type, restricted areas)
- Identify Sites and Activities of Interest (sampling, equipment deployment/setup)
- Identify initial possible traverse(s)
- Evaluate Path Dependent Surface Conditions and Accessibility (surface visibility, sun angles, shadowing, slopes, heat balance)
- Perform Flight Rule Validation
- Modify or Accept the Traverse Plan
- Communicate the Traverse Plan (enable coordination)

Traverse Example: Rover Traverse

Goal: Traverse from home base to remote site while deploying sensor probe / communication relay network linking the two sites.

(Crater Lake used as analog terrain.)



Traverse Example: Rover Traverse

Slopes limited to [0 20] degrees.

Nominal traverse velocity 0.5 m/s.

Effective antenna height 1.5 m (rover and sensor/communication wands).

Nominal communication range of 1 km.

Rover energy expenditure model

- 50 kg rover
- Flat surface: 0.216 Ws/m/kg + 5 W baseline
- Slopes: 0.0263 Ws/m/kg/deg; 30% energy recovery on downhill slopes
- Model based on Lunar Roving Vehicle

Traverse Example: Rover Traverse

Strategy for traverse planning and execution

```
do while and(not(mission accomplished), not(give up))
   compute visible region of surface
   compute minimum cost traverse to destination
   if minimum cost traverse contains a visible location
      traverse to visible location
      deploy a data wand
      if and(previous wand visible, target visible)
         mission accomplished
      else if previous wand not visible
         give up
loop
```

Traverse Example: Rover Traverse

Example Minimum Cost Traverse

Traverse Example: Rover Traverse

```
INITIALIZING ROVER SIMULATION

ROVER STATE: id=1 x=558671 y=4743633 z=1874 kJ=0 t=0
NETWORK STATE: Nodes released=0 SourceVisible=1 TargetVisible=0 NodesConnected=1
MeanCost=NaN
ROVER IDENTIFIED NEXT COMM/SENSOR NODE at X: 556985 Y: 4742685 Z: 1908
ROVER TRAVERSING FROM X: 558671 Y: 4743633 Z: 1874 to X: 556985 Y: 4742685 Z: 1908

ROVER STATE: id=2 x=556985 y=4742685 z=1908 kJ=34 t=0
NETWORK STATE: Nodes released=1 SourceVisible=1 TargetVisible=0 NodesConnected=2
MeanCost=1.25
ROVER IDENTIFIED NEXT COMM/SENSOR NODE at X: 557465 Y: 4741885 Z: 2033
ROVER TRAVERSING FROM X: 556985 Y: 4742685 Z: 1908 to X: 557465 Y: 4741885 Z: 2033

ROVER STATE: id=3 x=557465 y=4741885 z=2033 kJ=65 t=0
NETWORK STATE: Nodes released=2 SourceVisible=1 TargetVisible=0 NodesConnected=3
MeanCost=1.16
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
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ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR 1ST TRAVERSE
POINT
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, GIVING UP
```
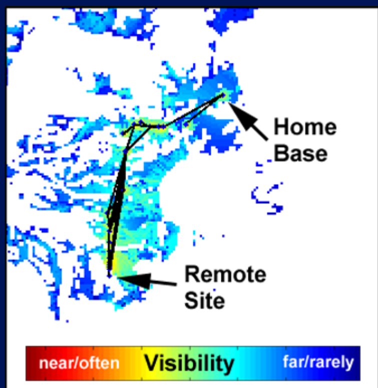
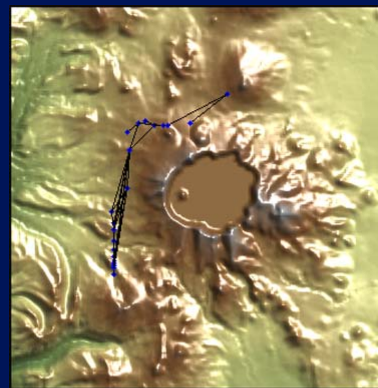

Traverse Example: Rover Traverse

An Example of a Successful Traverse





Apollo Voice Communications